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DIRECT TRANSFORMATION OF ENERGY WITH THE HELP OF FUEL ELEMENTS AND THE FUTURE OF THEIR USE IN RR TRANSPORT

V. A. Taft, et al

Foreign Technology Division
Wright-Patterson Air Force Base, Ohio

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by

V. A. Taft and F. Ya. Liebermann

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DIRECT TRANSFORMATION OF ENERGY WITH THE HELP OF FUEL ELEMENTS AND THE FUTURE OF THEIR USE IN RR TRANSPORT

Doctor of Technical Sciences Prof. V. A. Taft
Master of Technical Sciences F. Ya. Liebermann

On the basis of the achievements of contemporary physics, chemistry, and technology, the direct transformation of thermal energy into electric has become a technical reality at present. And although not many of the new energy sources go beyond the framework of the laboratory of the first industrial models, the different branches of industry have already initiated preparation for serious changes connected with the approaching upheaval in the methods of obtaining electrical energy.

The properties of the individual forms of new transformers - compactness, economy, capacity for overloads - answer precisely those requirements which are demanded of energy sources for rail transport just as for other (space, marine, and automobile) transportation systems.

In connection with this the posing of the question concerning the future of the utilization of new methods of energy conversion in rail transport is timely.

Of the different possible methods of direct transformation of energy the most developed at present are the following trends:

1) the conversion of chemical energy into electric - fuel elements;

2) the conversion of thermal energy into electric with the help of thermal converters;

3) the conversion of thermal energy into electric with the help of thermionic generators;

4) the magnetodynamic method of conversion.

Of the methods enumerated above the first two methods are most promising for future use in the field of transportation, since the third method is connected with high drops in temperatures, and the last one requires the development of powerful fixed installations.

In connection with this in relation to the assigned task the chemical method of the direct transformation of energy on the basis of fuel elements is examined below on the basis of foreign literature.

The fuel elements (TE) are the electrotechnical installations which work on gaseous, liquid, or solid fuel and which convert the chemical energy of the fuel into electric. Thus they can be considered as installations intended for the more effective combustion of fuel.

Unlike the usual process of burning, during which the chaotic transition of electrons from the molecules of fuel to oxidizer takes place, in the TE this process is spatially organized. The electrons pass over from the fuel to the oxidizer through the external electric circuit, and the ions appearing during oxidation and reduction are moved in the electrolyte between the electrodes and interact with each other, forming the products of oxidation of the fuel.

Table 1 gives the values of theoretical emf and efficiency for the basic current-forming TE reactions.

Table 1.

(1) Токообразующая реакция	300°K		500°K		1000°K	
	η, %	U, в	η, %	U, в	η, %	U, в
$C + O_2 = 2CO_2$	99,8	1,02	99,5	1,02	99	1,01
$2CO + O_2 = 2CO_2$	90,5	1,34	84	1,24	67,7	0,99
$2H_2 + O_2 = 2H_2O$	94	1,23	90	1,13	77	0,99
$CH_4 + 2O_2 = CO_2 + 2H_2O$	100	1,04	100	1,04	100	1,04
$N_2H_4 + O_2 = N_2 + 2H_2O$	100	1,56	100	1,56	~100	1,56

KEY: (1) Current-forming reaction.

The data in Table 1 show that the operating principle of the TE makes it possible to convert the chemical energy of fuel with a very high efficiency into the electrical energy of low-voltage direct current. Moreover the collection of separate fuel elements (modules) into batteries of significant power is feasible.

Real efficiency of a TE is somewhat lower than theoretical due to losses and expenditures of energy for the driving of accessory equipment and is 50-60%; however, even this value considerably exceeds the efficiency of conventional heat engines.

Types and designs of TE are very different. They are classified according to different features:

1) depending on the state of aggregation of fuel there are liquid, solid, and gas TE;

2) depending on the form of electrolyte - with liquid, molten, and solid electrolyte;

3) in dependence on temperature and pressure - high-temperature and low-temperature TE, high and low pressure TE;

4) on possible utilization TE can be used both as the electric power sources, and as storage batteries (reversible TE).

Below a brief survey is given of low-temperature TE of low pressure, which as a result of the simplicity of construction are most promising for transport use.

Gaseous oxyhydrogen TE have gained wide acceptance. The layout of one of such elements is given in Fig. 1.

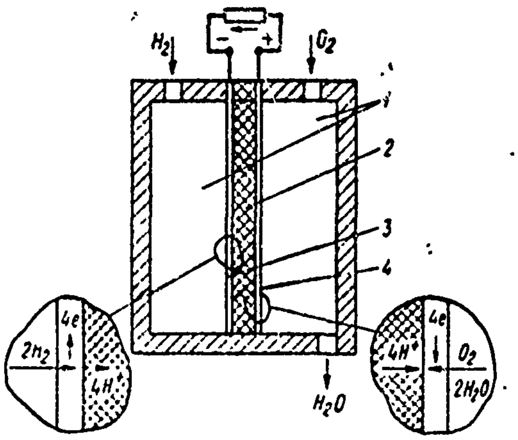

Fig. 1.

Two chambers of element 1, into which the oxygen and hydrogen are introduced, are divided by an ion exchanging membrane with a thickness of approximately 1 mm, which passes the hydrogen ions, but is not permeable for oxygen. On anode 3 two molecules of hydrogen form the positive ions which pass to cathode 4 through the ion-conducting membrance, and the liberated electrons - through the external circuit.

$$2H_2 \rightarrow 4H^+ + 4\bar{e}.$$

On the cathode the hydrogen ions recombine with O_2 and with electrons

$$4e + 4H^+ + O_2 \rightarrow 2H_2O.$$

The water vapors are condensed and removed from the oxygen gas chamber. The overall reaction

$$H_2 + O_2 \rightarrow 2H_2O + 4\bar{e}.$$

The development of low-temperature hydrogen-oxygen TE, which operate at room temperature and pressures close to atmospheric

is being carried out by many firms of the USA, England, France and the FRG.

Some of them initiated the industrial production of such TE basically for military and space purposes, and also according to the reports of the firms - for automobile and rail transport [8].

Thus hydrogen-oxygen TE of the "General Electric" firm (USA) with a power of 2 kW were installed on the American "Gemini" spaceships and fulfilled two important functions simultaneously: the power supply for the ship and the supplying of the astronauts with water. In Sweden low-temperature H_2-O_2 TE with a power of 200 kW are being developed for utilization on submarines. They assume to store the H_2 of these TE on the subs in the form of NH_3; O_2 - in a liquified state. Figure 2 gives the photograph of the fuel element of firm Chloride Technical Service (England). The fuel element has an external shape in the form of a conventional storage battery.

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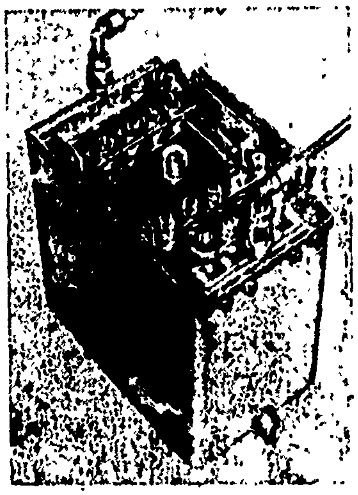


Fig. 2.

On the average the low-temperature hydrogen-oxygen TE are characterized by the following indices:

1) current density 100-500 mA/cm^2;

2) duration of operation 5 000 h;

3) specific weight power 40-60 kg/kW at a temperature of 20°C and approximately 30 kg/kW at higher temperatures (in the future for the utilization of light tanks for H_2 and O_2 - 5-10 kg/kW);

4) specific volumetric density taking into account the accessory equipment 50-100 dm^3/kW (in the future - 5 dm^3/kW);

5) efficiency taking into account expenditures of energy for running the accessory equipment 50-60%;

6) general cost of 250 rubles/kW;

7) cost of fuel 0.25 kopecks/kW h.

A significant shortcoming of hydrogen-oxygen TE is the need for heavy metallic tanks for the storage of compressed gases, their explosiveness, high cost, and the inconvenience of storage and transport, which are especially adverse for the future use of TE in the field of transportation.

In connection with this for the last two - three years at rapid rates fuel elements with liquid fuel began to be developed. The principle of their action is based on the obtaining of hydrogen by means of the decomposition of compounds which contain hydrogen upon their entry into the element. Such compounds include hydrazine (N_2H_4), methanol (CH_3OH), ethylene-glycol ($CH_2OH \cdot CH_2OH$), etc.

Figure 3 shows a schematic diagram of a liquid TE [2]. The fuel is methanol or ethylene-glychol dissolved in an alkaline electrolyte of KOH. The electrodes of the element possess different chemical activity in respect to the fuel mixture. The oxygen electrode is active only relative to oxygen and does not react with the fuel; in order to eliminate the oxidation of fuel on the surface of the electrode, this electrode is frequently made from porous carbon.

The second electrode is covered with a dehydrogenating catalyst of high activity (platinum, palladium, cobalt, etc.), which selects the hydrogen ions and introduces them into the electrode.

Figure 4 gives the photograph of a laboratory model of a methanol - air TE developed by the French Petroleum Institute [4].

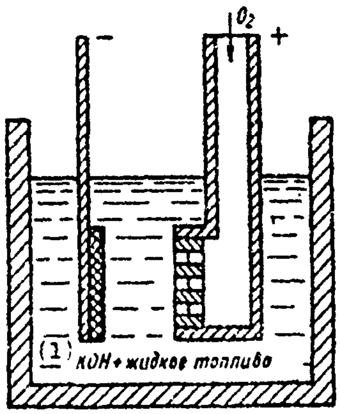


Fig. 3.
KEY: (1) KOH + liquid fuel.

The TE consists of 10 elements and has a total power of 10 W (I = 2.5 A; U = 4 V). The electrolyte - fuel mixture enters through the heat exchanger arranged above the elements and supplies each of them through pliable tubes.

Figure 5 gives the separate parts of this element (from left to right): air electrode made of porous carbon, hermetic seal, holder of electrode with connected tubes for the output of the fuel - electrolyte mixture, seal, fuel electrode covered with a catalyst - blackened platinum.

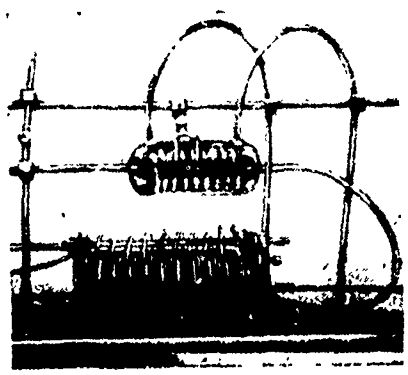


Fig. 4.

In 1964 in England the Shell firm demonstrated an autonomous power plant on a methanol-air TE with a total power of 5 kW. The arrangement powered an electric pneumatic hammer and together with the fuel supply for 12 hours of continuous operation was mounted in the body of a vehicle with a load capacity of 0.7 T.

In the USA liquid TE are being developed intensively for military purposes; in particular, TE batteries on hydrazine are being developed for power supply through the inverter of an alternating-current motor with a power of 2 hp. [3].

A hydrazil battery with a power of 3 kW was installed for advertising purposes as the power supply for a golf cart (Fig. 6). According to the firm of Allis-Chalmers a motoroller operated for 175 h [7].

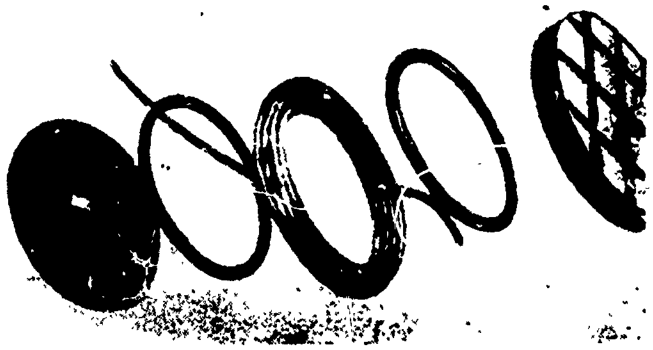


Fig. 5.

Economic indices of liquid TE are worsening considerably at present due to the action of two factors such as the high cost of fuel and the expensive catalysts of the electrodes.

However, there are all the bases for assuming that if liquid TE find wide industrial application, then basic changes will occur in the trends of development in the petroleum refining and chemical industry. An increase in the production of methanol and hydrazine will lead to a significant lowering in the costs of these fuels.

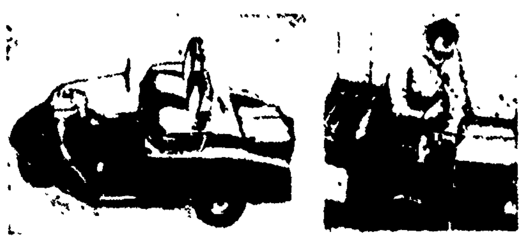


Fig. 6.

As concerns the expensive and scarce catalysts, i.e., platinum, palladium, silver, the expenditure of which is from 1 to 20 mgr per 1 cm^2 of electrodes, then one of the most important problems in the further perfection of liquid TE is the finding of cheaper and more active catalysts.

The improvement of the parameters of liquid TE is going on continuously at very rapid rates. This made it possible to outline the future of their development in the next 30-40 years, after accepting the condition that the progress in the perfection of

TE will proceed at the same rates as at present [4]. Table 2 gives basic data on the indices of operation of individual forms of liquid TE with the possibility for their further improvement.

A brief survey of the basic types of TE makes it possible to pass to the examination of their possible use in the field of transportation.

Table 2.

Тип ТЭ (1)	К.п.д. макс., % (2)	Вес, кг/квт (3)	Удельный объем, дм³/квт (4)	Стоимость установки, руб/квт (5)	Стоимость, коп/квт·ч (6)
(7) На метаноле (мощность 1 000 квт, ток 1 а); катализатор — платина					
1965 г. (12 мвт/см²) . . .	55	97	110—165	1 400	30
1970—1975 гг. (35 мвт/см²)	60	36	41—72	520	5,3
1985—2000 гг. (305 мвт/см²)	90	3,6—14	2,6—10	64	1,2
(8) На гидразине (мощность 100 квт, ток 1 а);					
1965 г. (105 мвт/см²). . . .	70	11—10	13—126	9 700	119
1970—1975 гг. (145 мвт/см²)	75	8,5—80	9,7—92	700	70
1985—2000 гг. (405 мвт/см²)	82	2,7—58	2—40	265	34

KEY: (1) Type of TE; (2) Efficiency max, %; (3) Weight, kg/kW; (4) Specific volume, dm^3/kW; (5) Cost of installation, ruble/kW; (6) Cost, kopeck/kW·h; (7) On methanol (power 1,000 kW, current 1 A); catalyst - platinum; (8) On hydrazine (power 100 kW, current 1 A). Designation: мвт/cm^2.

Transport, and in particular railroad, along with military and space technology, is considered one of the most promising branches for the utilization of fuel elements. Thus the international conference on the utilization of energy, which took place in Lozen in 1964, noted in its resolution that "fuel elements will receive their first major technical use probably in rail transport."

The questions of development of TE and the future of their use in the field of transportation were discussed at the joint session of the permanent commission of the Academy of Sciences

of the USSR on the scientific problems of the development of transport, which took place in July 1966, the scientific council of the Academy of Sciences of the USSR for fuel elements, and the scientific council of the Academy of Sciences of the USSR for complex problems of power engineering.

The future application of TE in the field of transportation is determined by such ov.lities as:

1) high efficiency;

2) favorable electrical characteristic for the powering of traction motors;

3) admissibility of heavy overloads;

4) rapid starting and comparatively long service life;

5) absence of exhaust gases.

Let us examine the basic technical and economical indices of TE which determine the possibilities for their application in transportation.

For a comparison the data on contemporary energy sources and on direct converters with the possibilities of the perfection of each in the next 30-40 years are given in Table 3.

The data in Table 3 confirm that the efficiency of fuel elements exceeds the possible efficiency of all other energy sources. This is one of the most important advantages of TE.

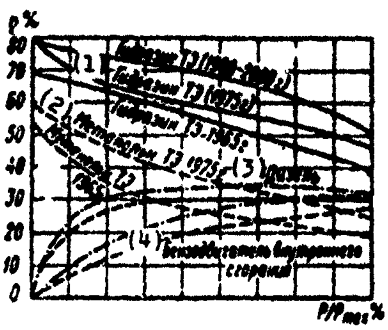
Special attention is merited by the nature of change in the efficiency of TE depending on the magnitude of load. Figure 7 gives the curves of change in the efficiency of liquid TE and for a comparison the efficiency of diesel engines depending on the

increase in the relative power given off by them, Fig. 8 - analogous curves with an increase up to 100 km/h in the velocity of a traction unit driven by an electric motor made from a TE [4]. Figures 7 and 8 show that with a dimunition in load the efficiency of a TE increases. Such a dependence is very favorable from the viewpoint of utilization of TE in the field of transportation.

Table 3.

(1) Вид двигателя (1)	1965 г.				1970—1980 гг.			
	(2) Вес, кг/квт	(3) Удельный объем, дм³/квт	(4) Стоимость, руб/квт	(5) К. п. д. макс., %	(2) Вес, кг/квт	(3) Удельный объем, дм³/квт	(4) Стоимость, руб/квт	(5) К. п. д. макс., %
(6) Дизельный двигатель	3—9	4—10	9,0—18	35—45	2—6	2,5—7	6,4—12	40—50
(7) Двигатель внутреннего сгорания (на бензине)	1,5—3	3—4	3,7—7,3	30—55	1—2	2—3	2,7—4,6	35—40
(8) Реактивный бензодвигатель	0,5—1	0,5—2	3,7	25—30	0,3—0,6	0,4—1,3	2,7	35—40
(9) Газовая турбина	0,3—0,5	2—3	9	20—25	0,2—0,3	1,5—2	6,4	30—45
(10) Свинцовый аккумулятор, 5-часовой разряд . . .	600	330	165	21	—	—	—	—
(11) Аккумулятор, 5-часовой разряд	200	100	530	15	—	—	—	—
(11) Аккумулятор, 4-часовой разряд	150	120	260	—	—	—	—	—
(12) Топливные элементы $H_2 - O_2$	40—60	50—100	450	50—70	5	5	50	80—85
(13) Топливные элементы на метаноле	97	110	1 400	55	14—3,6	10—2,6	64	80—90
(14) Топливные элементы на гидразине	110	126	730	70	58—2,7	40—2	265	80—90
(15) Термоэлектрические преобразователи	20—60	—	—	2—16	—	—	—	20
(16) Термоэлектронные преобразователи	1—16	—	—	11—17	—	—	—	30

KEY: (1) Type of engine; (2) Weight, kg/kW; (3) Specific volume, dm³/kW; (4) Cost, ruble/kW; (5) Efficiency, max, %; (6) Diesel engine; (7) Internal combustion engine (on gasoline); (8) Jet gasoline engine; (9) Gas turbine; (10) Lead battery, 5-h discharge; (11) Storage battery, 5-hour discharge; (12) Fuel elements H_2-O_2; (13) Fuel elements on methanol; (14) Fuel elements on hydrazine; (15) Thermal converters; (16) Thermionic generators.



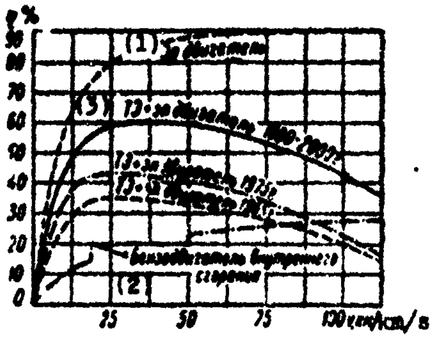


Fig. 7. Fig. 8.

Fig. 7.
KEY: (1) Hydrazine TE; (2) Methanol TE; (3) Diesel; (4) Internal combustion gasoline engine;

Fig. 8.
KEY: (1) El. motor; (2) Internal combustion gasoline engine; (3) TE + el. motor.

The use of TE on transport aggregates makes it possible to somewhat improve the traction indices of these aggregates in connection with the fact that TE are capable of three-fourfold overloads, whereupon with an increase in the current density the voltage across the terminals of the TE decreases considerably (Fig. 9). The maximum current load of a TE will probably be selected near the maximum permissible values of current [6].

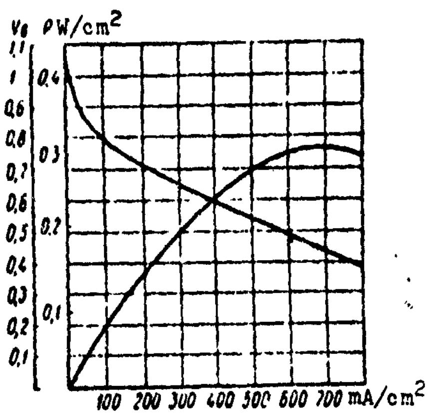


Fig. 9.

As concerns the weight and volumetric indices of TE, then on the contemporary level of their technical development it is difficult to give conclusions about dimensions and weight of TE of medium and high power. The weight and volumetric indices for TE given in Table 3 are obtained from an analysis of the data only of the first industrial models of TE. Table 3 shows that in weight and volume TE thus far are still considerably inferior to heat engines; in the future they probably can compete with them. Already at present TE have better indices in comparison with storage batteries.

Table 4 additionally gives comparative weight induces of hydrogen-oxygen fuel elements TE, accumulator batteries and a gasoline engine 20 kW in power [8].

As is evident from Table 4, with an increase in the electrical capacitance of the battery its weight increases almost proportionally, whereas the weight of a reversible TE remains constant and only the quantity of fuel consumed by it is increased. According to Table 4 already under the condition of operating for one hour the weight of oxyhydrogen TE is less than that of a storage battery and for 5-hour operation the TE has better volumetric indices.

Thus both in weight and volume and in efficiency TE already at present can compete successfully with contemporary storage batteries, especially during prolonged discharge.

Table 4.

(1) Вид источника энергии	(2) Водородно-кислородные ТЭ			(3) Аккумуляторный агрегат			Бензодвигатель (4)		
(5) Длительность работы, ч	1	5	10	1	5	10	1	5	10
(6) Вес, кг	1 000	1 000	1 000	1 500	5 000	9 000	200	200	200
(7) Объем, дм³	1 000	1 000	1 000	600	2 000	3 800	—	—	—
(8) Вес источника питания, кг	100	500	1 000	—	—	—	10	50	100
(9) Объем, дм³	100	500	1 000	—	—	—	—	—	—
(10) Общий вес, кг	1 100	1 500	2 000	1 500	5 000	9 000	210	250	300
(11) Общий объем, дм³	1 100	1 500	2 000	600	2 000	3 800	—	—	—

KEY: (1) Form of energy source; (2) Hydrogen-oxygen TE; (3) Battery aggregate; (4) Gasoline engine; (5) Duration of operation, h; (6) Weight, kg; (7) Volume, dm³; (8) Weight of power source, kg; (9) Volume, dm³; (10) Total weight, kg; (11) Total volume, dm³.

This gives grounds to assume that TE can find use in the field of transportation as stationary storage batteries, in particular for powering of installations for STsB and communication [СЦБ - signalization, centralization and block system],

and also for power supply of nonelectrified railroad consumers (stations, transportation buildings, etc.). Precisely in such a manner - for the power supply of homes - in the USA it is planned to use H_2-O_2 TE with a power of 500 W and higher. The possibility of utilization of TE as autonomous energy sources for the power supply of railroad cars is very tempting.

In the more distant future the use of liquid TE on battery transport units is possible. The possibilities of such use was indicated in a number of foreign investigations.

According to best indices of Table 3 the weights and volumes of fuel elements for the powering of the traction motors of a locomotive with a power of 2,000 kW are (Tab. 5):

Table 5.

(1) Вид ТЭ	1965 г.		1980—2000 гг.	
	(2) Вес, m	(3) Объем, $м^3$	(2) Вес, m	(3) Объем, $м^3$
(4) ТЭ на метаноле	194	220	7,2	5,2
(5) ТЭ на гидразине . . .	220	252	5,4	4
(6) Водородно-кислородные ТЭ	80	100	10	10

KEY: (1) Type of TE; (2) Weight, t; (3) Volume m^3; (4) TE on methanol; (5) TE on hydrazine; (6) Hydrogen-oxygen TE.

However, at present there are virtually still no acceptable constructions of TE for electric traction.

For use on locomotives TE should satisfy a number of specific requirements determined by the specific nature of rail transport, namely:

1) possess high reliability and be resistant to vibrations;

2) use inexpensive forms of liquid or solid fuel and air as an oxidizer, working at low temperatures and pressures;

3) have comparatively small volume and weight on the order of 10 20 kg/kW;

4) possess a large overload capacity and easily carry the "shocks" of load;

5) have minimum accessory equipment and be simple in operation.

The survey carried out on the state of the question of the direct transformation of energy with the help of TE and thermal converters makes it possible to make the following conclusions in connection with the possibility of the incorporation of these methods in the field of transportation:

1) with their further development TE can find use in the field of transportation;

a) as autonomous energy sources for the power supply of railroad cars;

b) as storage batteries of energy and for the powering of nonelectrified railroad consumers (reversible TE);

c) as an energy source called to substitute for an internal combustion engine on a locomotive;

2) at present for the preparation for wide utilization of TE subsequently it is advantageous to have:

a) extensive conducting of technical and economic investigations of the questions connected with the preparation for incorporation of TE in the field of transportation;

b) the creation of experimental station-storage batteries on the basis of liquid and oxyhydrogen elements.

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<u>The use of the method of the weakest link for the accelerated tests of radio-electronic circuits for reliability</u>. Boritskaya L. N., "Calculation and reliability of electronic devices". Trudy MIITa, Issue 261, 1968, pg. 79-90.

The method of calculation of a circuit based on the worst combination of parameters is examined; the criterion of the equivalency of effects necessary for the selection of laboratory test conditions equivalent to the actual conditions of operation is derived.

Tables 1, references 3.

<u>The use of the method of logarithmic characteristics for the calculation of transient processes in circuits with periodically</u>

changing parameters. Taft, V. A., Krepkaya K. A., "Calculation and reliability of electronic devices". Trudy MIITa, issue 261 1968, pg. 91-99.

In the article a grapho-analytic method is given for the calculation of transient processes in circuits with periodically changing parameters. Comparative transient characteristics are given which are obtained by the numerical method on a computer and by the grapho-analytic method. Figures 4, references 6.

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A general method is given for the calculation of a thermionic converter which works from the exhaust gases of an engine (TEG). Specific examples of the calculation for the 10D100 diesel are examined. Figures 6, references 6.

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The circuit of an electron level gauge intended for the calculation of bulk material during its loading is given. The instrument is built on semiconductor digital elements. Figures 1.

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